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Time Lens Based Single-Shot Ultrafast Waveform Recording: From High Repetition Rate to High Dynamic Range

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Abstract: The design and performance of a time lens-based, single-shot, ultrafast waveform recording system with sub-picosecond resolution and 200-ps record length is presented. The system evolved from recording rapidly changing waveforms at 104 Mframes/sec with limited dynamic range to a >20 dB dynamic range system capturing single events. Latest results demonstrate its integration with a new ultrafast optically-modulating x-ray sensor.

I. INTRODUCTION

Capturing arbitrary waveforms with < 1-ps detail and several hundreds of ps record length is a challenging problem, particularly when from a single event. The problem is compounded when the waveform originates from a space-constrained and/or hazardous environment, mandating remote recording away from the measurement. Two classes of this problem have been addressed using a time lens-based recoding system. In the first class, packets (or frames) arrive continuously at high frame rates and need to be recorded single-shot. Dynamic range (DR) and signal-to-noise ratio (SNR) requirements are low. In the second, only one high-value event occurs and the highest possible SNR and DR is desired. The system presented here was initially demonstrated at high repetition rate[1,2] and later modified for the high-DR application.

Time lens signal manipulation is based on an analogy between paraxial diffraction and narrow-band dispersion.[3] These processes introduce a quadratic frequency domain phase, scaling as $\xi\beta'' = \phi''$ for dispersion, where ξ is a distance and β'' is the group-velocity dispersion.

A lens imparts a quadratic phase in either space or time. The imparted time lens phase (equivalent to a linear frequency chirp $d\omega/d\tau$) is characterized by the temporal focal distance ξ_f or focal group delay dispersion (GDD), $\phi''_f = \xi_f \beta'' = -(d\omega/d\tau)^{-1}$, required for removal of the quadratic phase imparted by the time lens. In this work the phase is imparted through optical frequency mixing of the signal with a chirped pump pulse.[4]

A temporal imaging system is created by cascading input GDD ϕ''_1, a time lens, and output GDD ϕ''_2 in the proper balance to satisfy the imaging condition $1/\phi''_1 + 1/\phi''_2 = 1/\phi''_f$. The output waveform is a replica of the input waveform, magnified in time by $M = -\phi''_2/\phi''_1$. At focus, the input GDD $\phi''_1 = \phi''_f \cdot (1 - 1/M)$ is approximately equal to the focal GDD for large time magnification. Every high-rate occurrence of the time lens produces a magnified output waveform which can be recorded with a conventional recorder, at a resolution improved by the time magnification.[1,2]

Systems can also Fourier transform the input waveform. When $\phi''_1 = \phi''_f$, the output spectrum has the same envelope profile as the input time profile.[4] There is no need for output GDD; instead, a spectrometer maps the signal into space, enabling the waveform to be recorded on a high-DR camera. This produces a time-to-frequency followed by a frequency-to-space transformation. A single-event recording is produced by properly gating to obtain only one time lens exposure on the camera.

II. SYSTEM DESCRIPTION

Two recording systems are presented in Figs. 1 and 2 utilizing the same time lens and nearly identical input GDD paths. Each input contains optical fiber dispersion, and a Mach-Zehnder gated EDFA. The time lens is implemented through sum-frequency of a chirped pump with the dispersed signal in a periodically polled lithium niobate (PPLN) waveguide nonlinear mixing crystal.[1,2] The pump is generated from a 10 GHz optical comb source phase locked to the signal being recorded and pulsed picked down to a 50-104 MHz rate. The pulse train is compressed in a dispersion decreasing fiber to 240 fs, then dispersed and amplified to produce 200-pJ, 200-ps fwhm chirped pulses with $\phi''_f = -21.7\ \mathrm{ps}^2$.

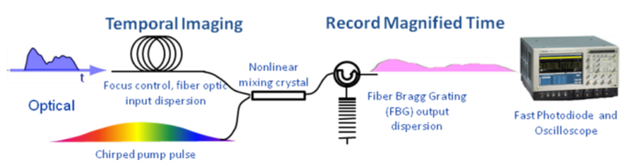

Fig. 1. High-rate system for time magnification.[1,2]

The original system[3] in Fig. 1 has $\phi''_1 = -22.2\ \mathrm{ps}^2$ and Fiber Bragg Gratings that produce an output dispersion of $\phi''_2 = -941\ \mathrm{ps}^2$. The -42.6X time magnified output waveform was recorded with a 20-GHz photodiode and oscilloscope. The signal was gated before amplification to optimize signal power for the recorded frames.

In Fig. 2, $\phi''_1 = \phi''_f$ and the FBG has been replaced with a spectrometer to map the output into space. The single-event signal from the sensor was dispersed, amplified, then gated before time lens mixing, minimizing integrated ASE. Initial optical testing without the sensor utilized a 0.5-m, 1200-groove/mm spectrometer and a PIXIS 100BR camera readout (see Fig. 4). The final design uses a 1-m, 1800-grove/mm spectrometer, a 470-μs duration MEMs based shutter, and a PIXIS 2048B camera to capture the output spectra (see Fig. 5). The sensor is a Fabry-Perot with a resonance that shifts due to the presence of x-ray generated (or optical) free carriers, acting as a fast modulator to an optical probe.[5] Optically driven test results are present here.

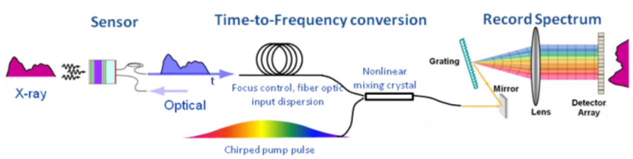

Fig. 2. Single-event system incorporating an x-ray-to-optical sensor[5], performing time-to-space mapping for high dynamic range recording.

III. RESULTS AND DISCUSSION

Earlier results with the system in Fig. 1 demonstrated the recording of pseudorandom < 1ps fwhm 3-pulse patterns at 104-Mframe/s.[3] That system is the foundation for the following results. The output FBGs were removed, the 0.5-m spectrometer added, and a 2.3% change to the input GDD was made to produce the system in Fig. 2 (without the sensor). The resulting time-to-space conversion was 0.75 ps/pixel with a spectrometer-limited impulse width of 1.6 ps fwhm. Fig. 4 shows single shot results attenuating an input 860 fs pulse over 30 dB. The 1% post pulse was verified with a cross-correlator.

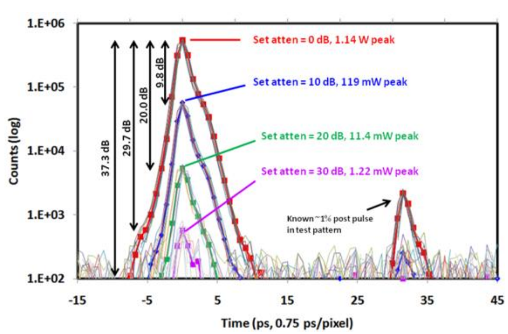

Fig. 4. Initial optical dynamic range testing of the system in Fig. 2, without the sensor.

The spectrometer and camera were upgraded to produce a 0.3 ps/pixel time-to-space conversion. A fast sensor was added and tested with a 100-fs optical impulse that served as a surrogate to future x-ray excitation. Results shown in Fig. 5 have a 885fs rising edge (spectrometer limited), an exponential tail, and is 2.5 ps fwhm, consistent with independent scanning pump-probe measurements of the sensor. In any fiber coupled recording system the power must be kept low enough to avoid nonlinear distortions in propagation. In Fig. 5 the normalized "1" power is 5mW reflecting off the sensor.

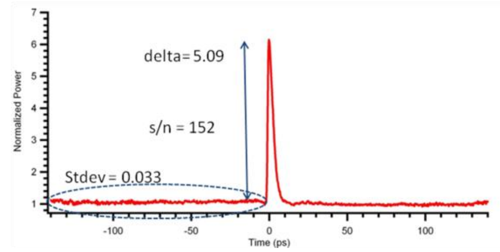

Fig. 5. Optical impulse testing of the combined sensor and recording system in Fig. 2.

IV. CONCLUSIONS

A time lens system has demonstrated single-shot measurements when operated in both a high rate readout and single-event, high-DR mode through minor changes to the input dispersion and modification of the final output. Integration with a fiber remoted sensor enables high-DR ultrafast x-ray waveform recording. Optical test results were discussed here. Details of the sensor and x-ray driven results are to be discussed in another paper.[6]

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